

Final Report

Title: Study of Cryogenic Complex Plasma

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AFOSR/AOARD Program Manager: Dr. R. Ponnappan

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14. ABSTRACT The charge state of dust particles in a plasma in a liquid helium vapor has been determined by the trajectory of dust particles under the application of electric field. The charging and discharging processes in cryogenic collision plasma have been studied. Two dimensional lattice waves have been identified for dust particles floating at the sheath edge and the bow wave formation has been observed in YCOPEX. Major results include 1. Measurement of charge state of dust particles by the method of oscillating motion of dust particles. The determining method is unique in a sense that particles dropped vertically in YD-1 about 1m in length and bounced up and down in the sheath without touching the bottom of the tube. 2. Measurement of charge state of dust particles in YD-2. Charge of dust particles in a cryogenic environment is found to be much smaller than those at room temperature. The smaller charge is explained by the collisionality of neutral particles in a liquid helium vapor plasma. 3. A large area complex plasma device YCOPEX is used to study basic parameters associated with dusty plasma like screening length. Dust-plasma interaction was studied in a two dimensional dust sheet.					
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ABSTRACT

This final report describes a progress during the period July 7, 2008 to July 6, 2010 on the contract of investigation entitled by “Study of Cryogenic Complex Plasma” (Principal investigator: O. Ishihara, AOARD 08-4116 Grant No. FA2386-08-1-4116). The research has been carried out at the Complex Plasma Lab of Yokohama National University in Yokohama, Japan. Research personnel include a principal investigator Osamu Ishihara, a senior technical advisor Dr. Yoshiharu Nakamura, a research associate Dr. Masako Shindo, a research associate Dr. Yoshifumi Saitou, a postdoctoral fellow Dr. Nirab Adhikary, a doctoral student Mr. Wataru Sekine, several graduate students and senior undergraduate students. The cryogenic complex plasma experiments have been carried out by three Dewar bottles, YD-1 (Yokohama Dewar 1), YD-2 and YD-3 with liquid helium, while a room temperature complex plasma has been studied in a linear device YCOPEX (Yokohama Complex Plasma Experiment). The charge state of dust particles in a plasma in a liquid helium vapor has been determined by the trajectory of dust particles under the application of electric field. The charging and discharging processes in a cryogenic collisional plasma have been studied. Two dimensional lattice waves have been identified for dust particles floating at the sheath edge and the bow wave formation has been observed in a YCOPEX.

I. Objectives

Our main objects are to reveal charge states of dust particles in a complex plasma at a room temperature as well as in a cryogenic environment and to reveal novel features of a cryogenic complex plasma produced by a stable discharge above or in superfluid liquid helium.

II. Introduction

Small charged dust particles are often found in plasmas in space, like in the interstellar medium, in the cometary environment, in planetary magnetospheres and in the upper atmosphere. They are round or irregularly shaped grains of carbon, silicates or other material measuring on the order of a micron or a fraction of a micron across. Such small fine particles of micron sizes in space were studied by plasma physics pioneers Lyman Spitzer, Hannes Alfvén and Irving Langmuir. As early as 1920s, Langmuir described the observation of a dusty plasma. In 1940s Spitzer discussed charging process of dust grains in the interstellar space and suggested the possibility of the presence of dust grains with both negative and positive charges in a plasma. Positive charges are present because of photoelectric emission by the UV light, while dust grains could be negatively charged because of the plasma particles (fast moving electrons and slow moving ions) arriving at and absorbed by dust particles. In 1950s, Alfvén suggested that the ionized gas condenses into small grains, resulting in formation of planets by agglomeration of these grains. Alfvén considered that the process of the agglomeration was interrupted and stayed as the asteroids and the Saturnian ring system.

Much later, the interests in dusty plasmas got an attention through the observation in the processing in reactive plasmas in the semiconductor industry in 1980s. The research in contamination control revealed that the particulate contamination of silicon substrates was produced from the plasma itself rather than from the external contaminated air. The micron size particles conveniently called dust particles were formed and grew in the gas through aggregation. They were forming a cloud electrically levitated above the wafer and fell on the wafer when the applied voltage on the wafer was turned off.

The Coulomb lattice was discovered in 1994 in a form of Coulomb crystal, where dust particles in a plasma form regular structures. Experimental discoveries of Coulomb crystals in laboratory dusty plasmas rekindled the interest of Coulomb lattice formation and recent research on plasma crystallization includes the study of phase transitions, lattice defects and others. Since micron size dust particles in laboratory plasmas could accumulate thousands of electrons on the surface, the resulting Coulomb repulsion between charged dust grains is expected to be strong. Dusty plasma is now known as a complex plasma which characterizes a complex system in which charged dust particles interact with plasmas. Recent progress on the physics of complex plasma is reviewed by the present principal investigator (O. Ishihara, Complex Plasma : Dusts in Plasma, Journal of

Physics D: Appl. Phys. **40**, R121-R147 (2007)).

Recent advances in the study of a complex (dusty) plasma have been developed in space plasma, cosmic plasma, laboratory plasma, fusion plasma as well as industrial plasmas. A cryogenic complex plasma is an emerging field to study dust-plasma interaction in such an extreme condition as cryogenic temperature. Our earlier experiments suggested the possible production of cryogenic plasma in liquid helium environments. The theoretical study of a complex plasma in the cryogenic environment suggested a unique nature of two-dimensional dust structure on the surface of liquid helium, while the cryogenic experimental studies revealed the low charge state of dust particles and the superdense state of dust structure. Our focus is the study of a complex plasma at the liquid helium temperature. Some of our results have been reviewed [O. Ishihara, Complex Plasma Research under Extreme Conditions, in *Multifacets of Dusty Plasmas*, edited by J.T. Mendonça, D. P. Resends and P. K. Shukla, AIP Conference Series, vol. 1041 (Melville, N.Y. : American Institute of Physics, 2008) pp. 139-142].

III. Experiments

(1) YD-1 Experiment

Experimental setup YD-1 is a glass tube contained in a silver-coated glass Dewar bottle (glass cryostat) with the inner diameter of 9.6 cm and the height of 80 cm. The Dewar bottle is filled with liquid helium or liquid nitrogen and is inserted in a liquid nitrogen stored in an outer Dewar bottle with the outer diameter of 20 cm. The silver coated Dewar bottles have 1 cm wide vertical uncoated slit for observational purpose. Figure 1 shows the glass tube inserted in the inner Dewar bottle. The typical glass tube is 70 cm in length consisting of a thin upper part of 60 cm in length with 1.6 cm in diameter and a thick lower part of 10 cm in length with 4.8 cm in diameter. Various sizes of glass tubes were used. The glass tube is connected to an external stainless steel pipe at the flange attached to the inner Dewar bottle. The temperature of the gas in the glass tube is controlled by the cryogenic liquid, liquid helium or liquid nitrogen, contained in the inner Dewar bottle. The outer Dewar bottle contains liquid nitrogen to maintain the inner cryogenic temperature. An rf helium plasma with a neutral gas pressure $P = 0.1 \sim 100$ Pa is produced by applying the rf (13.56 MHz) power of $1 \sim 7$ W between the electrodes mounted in the lower part of the glass tube. The plasma is characterized by the electron density of $n_e \sim 10^{15} \text{ m}^{-3}$ and electron temperature of a few eV, while ions lose their kinetic energy through collisions with cooled neutrals. Acrylic particles (dust particles) of $a = 0.4 \sim 10 \text{ }\mu\text{m}$ in radius with a mass density of $\rho_d = 1.2 \text{ g/cm}^3$ are dropped from the dust dropper situated about 80 cm high from the bottom of the glass tube. The dust particles charged in the plasma are suspended around an equilibrium position, about a few centimeters from the bottom of the tube, where the upward sheath electric force balances with the downward gravitational force. The particles illuminated by red ($\lambda = 671 \text{ nm}$) or green ($\lambda = 532 \text{ nm}$) laser are visible by naked eyes, while the motion of dust particles are recorded through the slit by a high-speed CCD camera at a frame rate of $200 \sim 400$ fps and analyzed by PTV (Particle Tracking Velocimetry) method. To observe vertical motion of dust

particles in the plasma, a few particles are dropped from the dust dropper. The dust particles are accelerated in the long glass tube under the gravity. The dust particles are immediately charged after entering the plasma, go further below the equilibrium position and go deeper in the sheath. Electric force acting upward on the charged dust particle in the sheath suspends the dust particle and the dust particle moves upward against gravity.

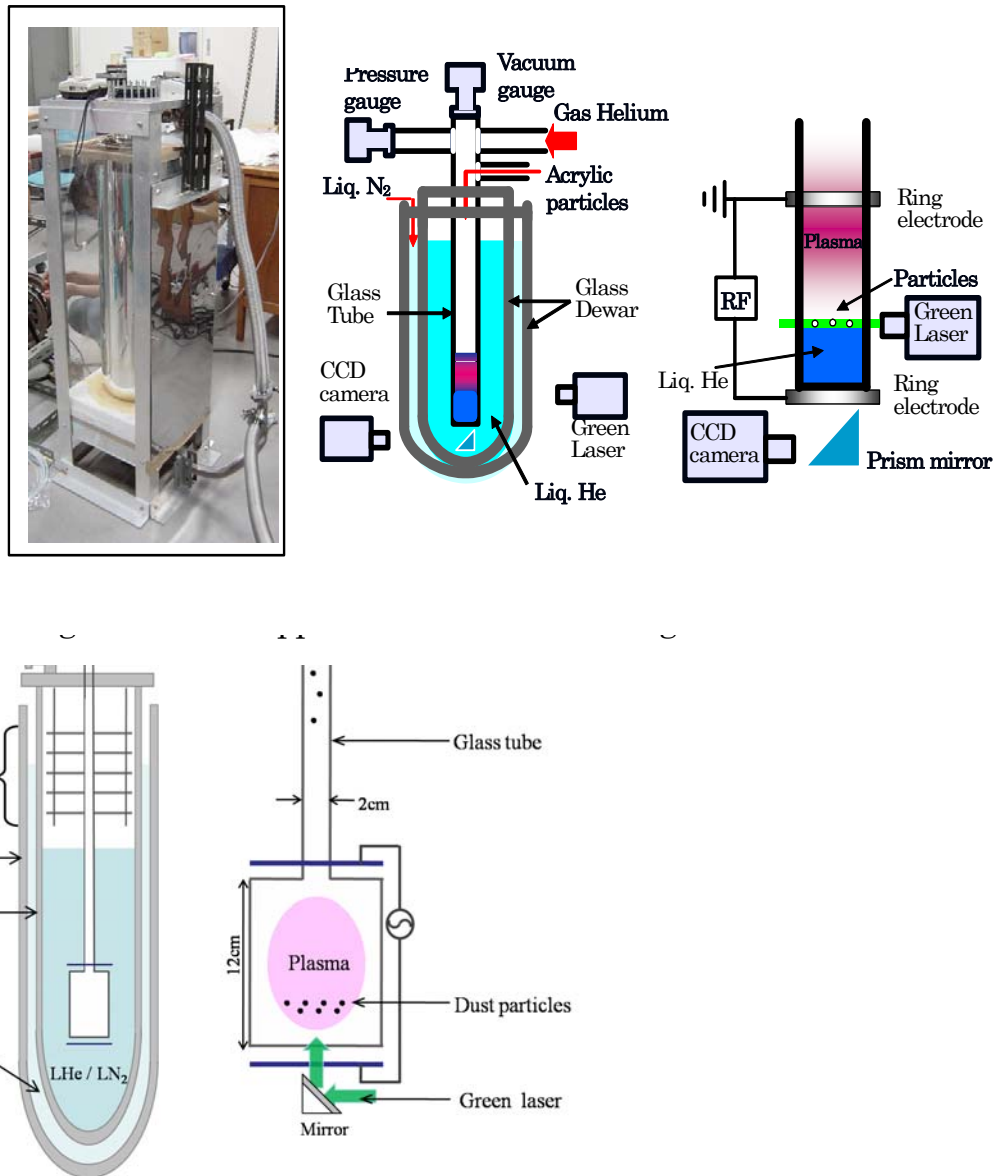


Fig. 1 YD-1 setup. (A) A straight glass tube. (B) A glass tube of 2 cm in diameter has larger volume of 12 cm in length at the end.

Charges of dust particles were determined by detecting the damped oscillations of dust particles in a cryogenic plasma.

As shown in Fig. 2 we have installed Helmholtz coil to apply the magnetic field in vertical direction. Motion of dust particles will be controlled by the application of the magnetic field.

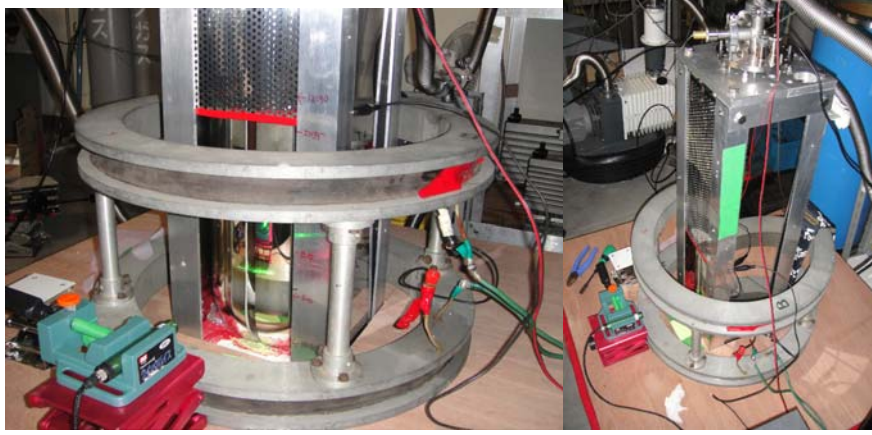


Fig. 2 Helmholtz coil of 25cm in diameter with 135 turns is installed for YD-1. The magnetic field up to 141 G at the current of 30A is measured.

(2) YD-2 Experiment

For the purpose of observing the interaction of a plasma and dust particles above the surface of liquid helium, we set up YD-2 (See Fig. 3) and produced a steady plasma above the liquid helium surface. The YD-2 silver-coated Dewar bottle is 16 cm in inner diameter and 1 m in height. The reflectors are installed to avoid external heat flow from the top flange as shown in Fig. 3. The liquid helium is kept in a superfluid state by decreasing the pressure below 0.1 atm. The discharge unit can be moved vertically to adjust the position of the needles from the liquid helium surface. The rf discharge plasma is produced by applying voltage (10kHz, ~6 kV) to tungsten wire needle electrodes. The plasma with neutral density of 10^{26} m^{-3} is produced locally near the electrodes in high gas pressure (6 ~ 8 kPa). Dust particles are introduced from the upper part of the Dewar bottle. Dust particles dropped from the dust dropper near the flange are gaining enough energy under the gravity before reaching the plasma region. Once dust particles are in a plasma, dust particles are charged and continue to move downward away from the plasma. Then charged dust particles enter the region of liquid helium vapor where two parallel plates produce electric field in the horizontal direction. The trajectories of charged dust particles are deflected by the electric field and are recorded by a CCD camera. We observed decharging process of dust particles by detecting the trajectories of dust particles coming out of the plasma in a cryogenic environment.

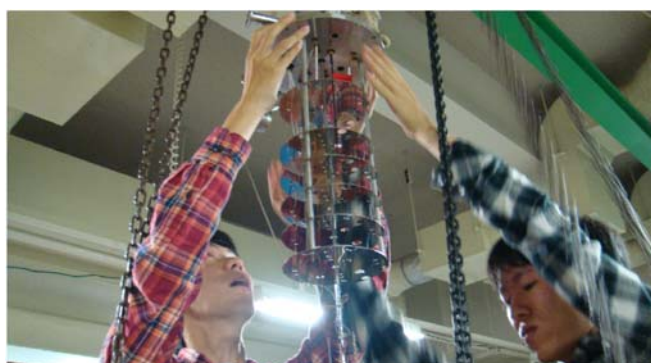


Fig. 3 Set up YD-2.

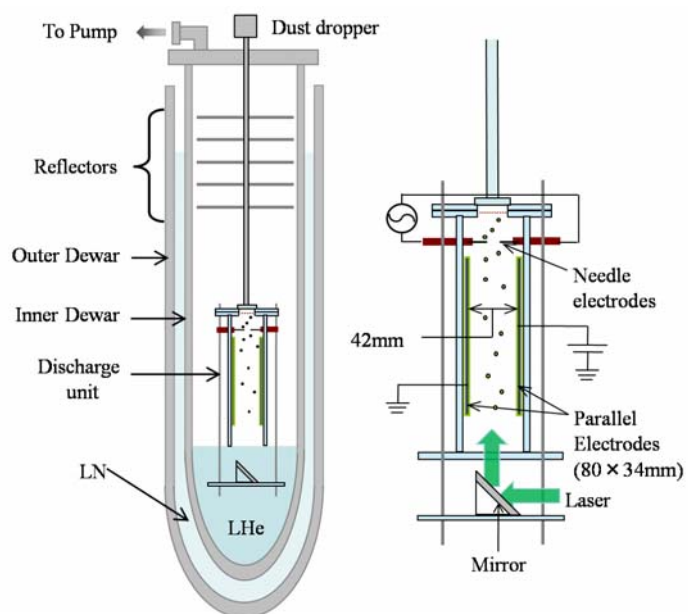


Fig. 4 YD-2. The plasma is produced in a vapor of liquid helium.

(3) YCOPEX

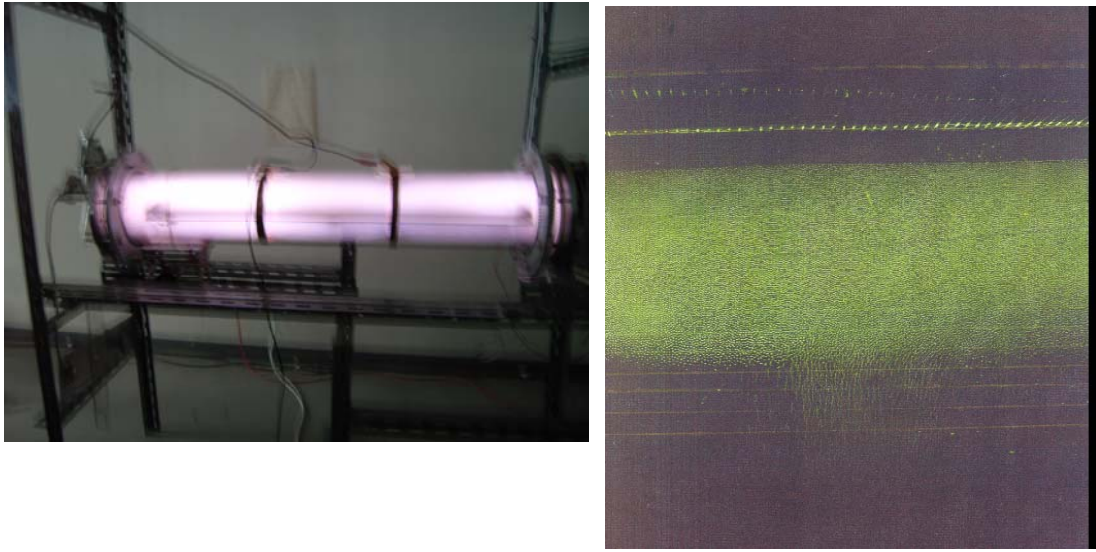


Fig. 5. YCOPEX. Linear device for the room temperature complex plasma. The right picture shows a dust cluster floating above the sheath.

Screening length around a dust particle is measured for the first time in a complex plasma (published in *Physics of Plasmas* (2009)).

(4) YD-3 experiment - new experimental device

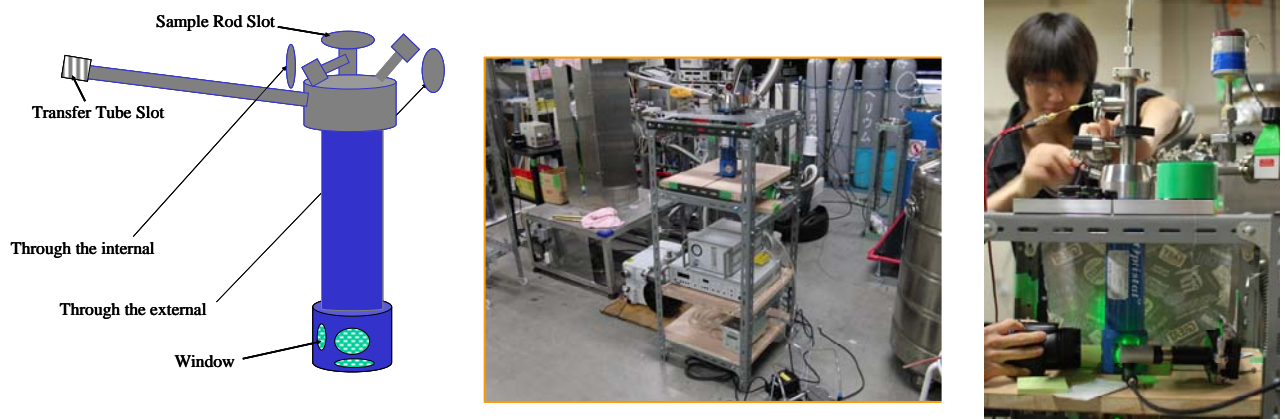


Fig. 6 YD-3 is installed to observe dust particles on the surface of liquid helium through a large window. The YD-3 is much smaller than YD-1 and YD-2 in a volume of liquid helium

IV. Results

Our major results include

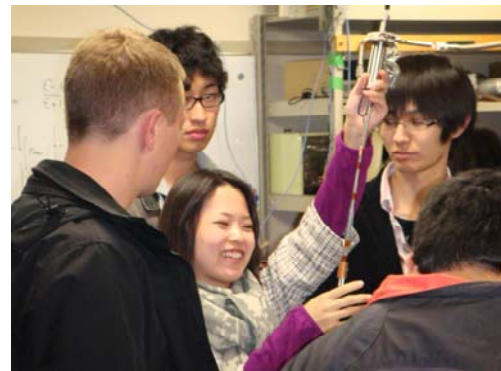
1. Measurement of charge state of dust particles by the method of oscillating motion of dust particles in a sheath in YD-1. The determining method is unique in a sense that particles dropped vertically in YD-1 about 1m in length and bounced up and down in the sheath without touching the bottom of the tube.
2. Measurement of charge state of dust particles in YD-2. Charge of dust particles in a cryogenic environment is found to be much smaller than those at room temperature. The smaller charge is explained by the collisionality of neutral particles in a liquid helium vapor plasma.
3. A large area complex plasma device YCOPEX is used to study basic parameters associated with dusty plasma like screening length. Dust-plasma interaction is studied in a two dimensional dust sheet.

V. Research assistants supported by AOARD

Three outstanding graduate students, Mr. Jumpei Kubota, Ms. Natsuko Uotani and Ms. Megumi Chikasue received research scholarships through the AOARD grant.



Mr. Jumpei Kubota at the center



Ms. Natsuko Uotani

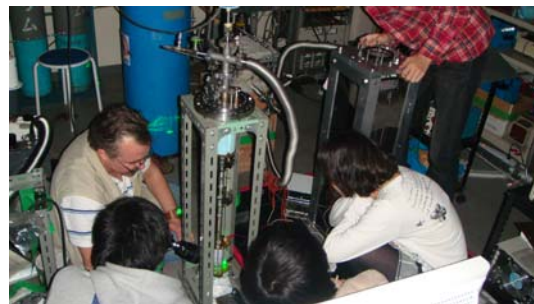
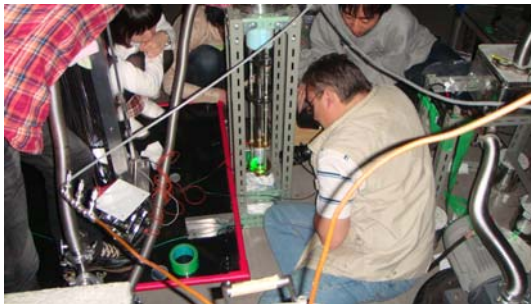


Ms. Megumi Chikasue

VI. Collaboration with the Complex Plasma Lab at University of Sydney (Australia), Complex Plasma Lab at Max Planck Institute (Germany) and University of California (USA).

1. **Dr. Alex Samarian**, Research Scientist at University of Sydney, Australia.

Visited and worked in our lab : March 17, 2009-April 14, 2009-11-25.



2. **Dr. Uwe Konopka** (Research Scientist, Max Planck Institute, Germany)

November 9, 2009-November 18, 2009.

3. **Dr. Marlene Rosenberg** of University of California, San Diego, USA

Published a joint paper: W. Sekine, O. Ishihara and M. Rosenberg, Dust dynamics in cryogenic environment, Journal of Plasma and Fusion Research Series 8, 290-293 (2009).

4. **Group visit from Max Planck Institute**, Germany and mini-workshop

November 24, 2009



Sergey Khrapak, Boris Klumov, Manis Chaudhuri, Lenaic Coüedel, Vladimir Nosenko, Slobodan Mitic, Ralf Heidemann, Robert Sütterlin

Yokohama Complex Plasma Seminar (November 24, 2009)

at Yokohama National University

PROGRAM

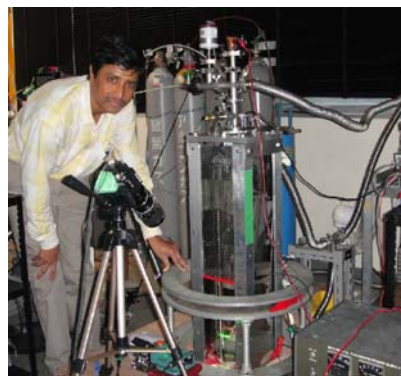
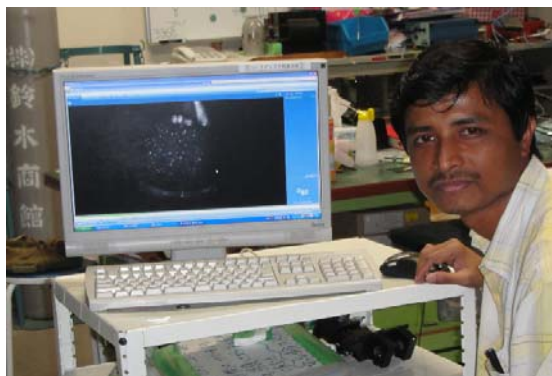
Welcome Osamu Ishihara

1. Sergey Khrapak, MP Recent progress in the theory of complex (dusty) plasmas
2. Boris Klumov, MP Structural properties of three-dimensional complex plasmas
3. Manis Chaudhuri, MP Ionization controlled interaction potential in collisional complex plasmas
4. Lenaic Coüedel, MP MD simulation of complex plasma crystal using CUDA
5. Vladimir Nosenko, MP Observation of frequency cutoff for dust acoustic waves
6. Slobodan Mitic, MP Spectroscopic evaluation of metastable density in complex plasma
7. Ralf Heidemann, MP Dark Solitons in Complex Plasmas
8. Yoshiharu Nakamura, YNU YCOPEX Experiment
9. Jumpei Kubota, YNU Overview-Cryogenic complex plasma experiments at YNU
10. Natuko Uotani, YNU Dust charging in a collisional plasma under cryogenic temperature
11. Masafumi Ueno, YNU Rotation of dust cluster in a plasma with magnetic field at cryogenic temperature
12. Robert Sütterlin, MP Structural Analysis Using Minkovsky Functionals
13. Hiroki Sakai, YNU YD3Experiment
14. Takahiro Wakiya, YNU Plasma parameters under cryogenic condition
15. Wataru Sekine, YNU Theory on cryogenic complex plasma
16. Megumi Chikasue, MP Thermal effect on charged dust particles in a plasma under cryogenic condition
17. Kei Takakura, YNU Charged dust particles in diffused plasma on liquid surface
18. Junya Okabe, YNU MHD simulation of magnetic reconnection in a cometary plasma

Closing Osamu Ishihara

NB MP=Max Planck Institute, YNU=Yokohama National University

5. Dr. Nirab Adhikary, a postdoctoral fellow from India



Dr. Nirab Adhikary from India works on YD-1 to see the magnetic field effect on the dust chain formation.

APPENDIX

A. Personnel Supported:

- (1) Osamu Ishihara, a principal investigator and a director of the Complex Plasma Lab at Yokohama National University
 - (2) Dr. Yoshiharu Nakamura,* a senior technical advisor, retired from ISAS (Institute of Space and Astronautical Science), JAXA (Japan Space Exploration Agency)
 - (3) Dr. Masako Shindo, a research associate
 - (4) Dr. Yoshifumi Saitou, a research associate
 - (5) Dr. Nirab Adhikary,* a postdoctoral fellow
 - (6) Mr. Wataru Sekine, a doctoral student who completed his PhD in March, 2010 with the dissertation Study on fundamental physics of dust particles in a complex plasma under cryogenic environment
 - (7) Research Assistants, graduate students, Mr. Jumpei Kubota (graduated in March, 2010), Ms. Natsuko Uotani and Ms. Megumi Chikasue
 - (8) Ms. Naomi Shibuya,* secretary
- * Salary is paid by the grant

B. Publications

1. Publications (Archival Documentation)

1. Y. Nakamura and O. Ishihara, A Complex plasma device of large surface area, Review of Scientific Instruments 79, 033504-1-033504-4 (2008).
2. C. Kojima, J. Kubota, Y. Tashima, and O. Ishihara, Dust Dynamics in Wake Channel, Proceedings of Third International Symposium on Physical Science in Space 2008, J. Jpn. Soc. Microgravity Appl. 25, 353-356 (2008).
3. O. Ishihara, Complex Plasma Research under Extreme Conditions, Multifacets of Dusty Plasmas, Fifth International Conference on the Physics of Dusty Plasmas (Ponta Delgada, Azores, Portugal, 18-23 May, 2008) edited by J.T. Mendonça, D. P. Resends and P. K. Shukla, AIP Conference Series, vol. 1041 (Melville, N.Y.: American Institute of Physics, 2008) pp. 139-142.
4. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Dust Charge in Cryogenic Environment, Multifacets of Dusty Plasmas, Fifth International Conference on the Physics of Dusty Plasmas, (Ponta Delgada, Azores, Portugal, 18-23 May, 2008) edited by J.T. Mendonça, D. P. Resends and P. K. Shukla, pp. 235-236.
5. M. Shindo and O. Ishihara, *Study of Complex Plasmas*, in Nano- and Micromaterials, ed. by K. Ohno, M. Tanaka, J. Takeda, and Y. Kawazoe (Springer Berlin Heidelberg, 2008), Chap. 13 (pp. 313-327).
6. Y. Nakamura and O. Ishihara, Measurements of electric charge and screening length of micro-particles, Physics of Plasmas, **16**, 043704-1-043704-5 (2009).
7. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Coulomb cluster in a plasma under cryogenic environment, Journal of Plasma and Fusion Research Series **8**, 286-289 (2009).
8. W. Sekine, O. Ishihara and M. Rosenberg, Dust dynamics in cryogenic environment, Journal of Plasma and Fusion Research Series **8**, 290-293 (2009).
9. Masako Shindo, Natsuko Uotani and Osamu Ishihara, Dust charge in collisional plasma in liquid helium vapor, Journal of Plasma and Fusion Research Series **8**, 294-297 (2009).

10. O. Ishihara, Complex plasmas in cryogenic environment in *Advances in plasma research at ultra-low temperature*, J. Plasma and Fusion Research) Vol. 85, 511-519 (2009). (in Japanese)
11. O. Ishihara, W. Sekine, J. Kubota, N. Uotani, M. Chikasue and M. Shindo, Experiments on Cryogenic Complex Plasma, in *New Developments in Nonlinear Plasma Physics*, ed. by B. Eliasson and P.K. Shukla, AIP Conf. Proc. (New York, 2009), pp.110-126.

C. Interactions/Presentations

1. Invited Talks

1. O. Ishihara, Dust structures in complex plasma, Satellite Meeting on Plasma Physics and Advanced Applications in ASO, Kumamoto, Japan. Sep. 12-14, 2008.
2. O. Ishihara, Complex Plasma Research in Yokohama, Institute of Experimental and Theoretical Physics, Al Farabi Kazakh National University (October 22, 2008, Almaty, Republic of Kazakhstan).
3. O. Ishihara, Cryogenic complex plasma experiment, International Symposium on Cutting Edge Plasma Physics (August, 2009, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy).

2. Conference Proceedings

1. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Observation of dusts structure in cryogenic environment (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan), FD • P3-029, p. 324.
2. Wataru Sekine, Osamu Ishihara and Marlene Rosenberg, Dust dynamics in cryogenic environment (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan), FD • P3-031, p. 325.
3. Masako Shindo, Natsuko Uotani and Osamu Ishihara, Dust charge in collisional plasma in liquid helium vapor (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan). FD • P3-032, p. 325.
4. Osamu Ishihara and Tetsuo Kamimura, Dust Structures in Complex Plasma, Satellite Meeting on Plasma Physics and Advanced Applications in ASO, ASO Ikoi-no-Mura, Aso, Kumamoto, Japan September 12-14, 2008.
5. O. Ishihara, Cryogenic Complex Plasma Experiment, International Symposium on Cutting Edge Plasma Physics (24-28 August, 2009, ICTP(The Abdus Salam International Centre for Theoretical Physics), Trieste, Italy)
6. W. Sekine and O. Ishihara, Cryogenic effect on dust grain charging in a plasma, The 7th General Scientific Assembly of the Asia Plasma and Fusion Association (APFA2009) (Aomori, Japan, during October 27-30 2009.)
7. N. Uotani, J. Kubota, M. Chikasue, W. Sekine, M. Shindo and O. Ishihara, Dust grain charging in a collisional plasma under cryogenic temperature, The 7th General Scientific Assembly of the Asia Plasma and Fusion Association (APFA2009) (Aomori, Japan, during October 27-30 2009.)

3. Domestic Workshop

1. J. Kubota, C. Kojima, K. Abe and O. Ishihara, Dust charge in a plasma surrounded by cryogenic liquid, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
2. Chikara Kojima, Jumpei Kubota, Keita Abe and Osamu Ishihara, Charged dust floatation on the surface of liquid helium, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
3. K. Abe, C. Kojima, J. Kubota, and O. Ishihara, Variation of a macroscopic physical quantity in the presence of dust particles in a plasma, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
4. Wataru Sekine and Osamu Ishihara, Charged dust particles on the surface of liquid helium, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
5. Y. Nakamura and O. Ishihara, Measurements of electric charge and screening length of micro-particles in a plasma sheath, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
6. N. Uotani, M. Shindo and O. Ishihara, Transition from dust charging in a plasma to discharging in helium gas, 9th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 18-19, 2008).
7. Y. Saitou, Y. Nakamura, and O. Ishihara, Interaction of the flow of dust particles in a plasma with a biased obstacle, 10th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 26-27, 2009).
8. K. Takakura, N. Uotani, M. Chikasue, J. Kubota and O. Ishihara, Charged dust particles in diffused plasma on liquid surface, 10th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 26-27, 2009).
9. M. Chikasue, N. Uotani, K. Takakura, M. Shindo and O. Ishihara, Thermal effect on charged dust particles in a plasma under cryogenic condition, 10th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 26-27, 2009).
10. M. Ueno, J. Kubota and O. Ishihara, Rotation of a dust cluster in a plasma with magnetic field at cryogenic temperature, 10th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 26-27, 2009).
11. A. Seto, T. Kamimura, Y. Saitou, Y. Nakamura and O. Ishihara, Simulation on Void Structure in the Flow of Dust Particles, 10th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 26-27, 2009).

D. Inventions

None

E. Honors/Awards

None